

# String production after angled brane inflation

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## Abstract

We describe string production after angled brane inflation. First, we point out that there was a discrepancy in previous discussions. The expected tension of the cosmic string calculated from the four-dimensional effective Lagrangian did not match the one obtained in the brane analysis. In the previous analysis, the cosmic string is assumed to correspond to the lower-dimensional daughter brane, which wraps the same compactified space as the original mother brane. In this case, however, the tension of the daughter brane cannot depend on the angle ( $\theta$ ). On the other hand, from the analysis of the effective Lagrangian for tachyon condensation, it is easy to see that the tension of the cosmic string must be proportional to  $\theta$ , when  $\theta \ll 1$ . This is an obvious discrepancy that must be explained by consideration of the explicit brane dynamics. In this paper, we will solve this problem by introducing a simple idea. We calculate the tension of the string in the two cases, which matches precisely. The cosmological constraint for angled inflation is relaxed, because the expected tension of the cosmic string becomes smaller than the one obtained in previous arguments, by a factor of  $\theta$ .

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# 1 Introduction

String theory is perhaps the most promising scenario where quantum gravity is included by the requirement of additional dimensions and supersymmetry. Models with more than four dimensions are interesting, since the idea of the large extra dimension[1] may solve or weaken the hierarchy problem.<sup>2</sup> In scenarios of large extra dimensions, the standard model fields are expected to be localized on a wall-like structure, while the graviton propagates in the bulk. In the context of string theory, the most natural embedding of this picture would be realized by a brane construction. These models are of course very interesting from the cosmological viewpoint. Inflation with such a situation is still an interesting problem[2, 3]. A model of defect inflation with large extra dimension is discussed in [4]. Other cosmological issues, in which defects play important roles, such as baryogenesis with a low fundamental scale are discussed in [5, 6, 7]. We think cosmological considerations with nonstatic brane configurations, such as brane defects or brane Q balls[8, 9] are very important, since we expect that future cosmological observations will reveal the cosmological evolution of the brane Universe. If one wants to know what kinds of brane defects are allowed to affect our present Universe, one should know how they were formed. In the original brane inflation scenario[11], the inflationary expansion is driven by the potential between D-branes and anti-D-branes evolving in the bulk space of the compactified dimensions. Then the brane inflationary scenario for branes at a fixed angle is studied in ref.[12], where the slow-roll condition is improved by a small angle. The end of brane inflation is induced by the brane collision where brane annihilation (or recombination) proceeds through tachyon condensation[13]. During brane inflation, the tachyon is trapped in the false vacuum, which may result in the formation of lower-dimensional branes after brane inflation. The production of cosmological defects during this process is discussed in ref.[12, 14], where it is concluded that cosmic strings are copiously produced in this scenario, but the formation of domain walls is seriously suppressed. Ref.[15], however, indicates that all kinds of defects would be produced and the conventional problems of cosmic domain walls and monopoles should arise. Later, in refs.[16, 17, 18], brane

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<sup>2</sup>Denoting the volume of the  $n$ -dimensional compact space by  $V_n$ , the observed Planck mass is obtained by the relation  $M_p^2 = M_*^{n+2} V_n$ , where  $M_*$  denotes the fundamental scale of gravity.

production was reexamined and the conclusions were different from [14] and [15].<sup>3</sup>

In this paper, we will examine the tension of the cosmic strings produced after angled brane inflation. Here we summarize the naive expectations and known facts.

- The model of angled brane inflation is expected to be a model of D-term inflation in the four-dimensional effective Lagrangian.
- A cosmic string that is produced after D-term inflation is examined in ref.[21], and is shown to satisfy the BPS conditions in a generic situation. The exact form of the tension of the D-term string is also calculated.

Thus, one would expect that the cosmic string that is produced after angled brane inflation is the D-term string that satisfies the BPS condition. If the above expectations are correct, the tension of the cosmic string should depend on the angle. On the other hand, however, the previous arguments on string formation after angled brane inflation did not support this expectation. For example, in refs.[14, 16], it is discussed that;

- The produced daughter brane must wrap around the same compactified space as the original mother brane. Thus, the calculated tension of the daughter brane does not depend on the angle.

This result does not support the above expectation. Moreover, one can calculate the tension of the cosmic string from the effective Lagrangian for tachyon condensation. The tension obtained from the tachyon effective Lagrangian does depend on the angle, which again does not support the argument in refs.[14, 16].

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<sup>3</sup>The actual phenomenological possibilities of cosmological brane defects in the brane world models are not confined within the above arguments. For example, in ref.[6], the enhancements of baryon number violation and baryogenesis that are mediated by cosmological defects are discussed for models with localized matter fields. Moreover, in ref.[19] and later in refs.[9, 20], it is argued that the fields that parameterize the position of the branes can fluctuate in four-dimensional space-time, and the fluctuation forms a cosmological defect. In ref.[19], the position of a brane in the fifth dimension is used to parameterize the Alice string in the effective four-dimensional space-time, and it was shown that the brane must smear in the core so that it resolves the anticipated singularity. Then in refs.[9] and [20], it is shown that the relative position of the branes in higher-dimensional bulk space could fluctuate in the four-dimensional space-time and could parameterize cosmological defects such as strings, domain walls, and Q balls.

In this paper, we will show that one can easily understand why there was such a discrepancy between the two calculations. Our result is that the tension of the produced cosmic string does depend on the angle, which is different from previous discussions. The final state of the produced daughter brane does not wrap the same compactified space as the original mother brane. However, here we should note that our result does not contradict to the previous arguments. We will consider the details of the recombination process of the original branes, and find that the daughter brane that wraps the same compactified space as the original mother brane would appear as the precedent state of the final brane configuration. The precedent brane configuration is then deformed into the final state, where the daughter brane is extended between recombined branes. The tension of the daughter brane now depends on the angle, which is consistent with the expectation from the effective Lagrangian.

In Sec. 2, we begin with a short review of an angled brane inflation model and the cosmic string production after inflation[14]. From the viewpoint of the effective Lagrangian, it is easy to see that the tension of the strings produced must depend on the angle  $\theta$ . In the previous arguments[14], however, it was assumed that the daughter brane wraps the same compactified space as the mother brane. On the basis of this assumption, the tension of the cosmic string was calculated and did not depend on  $\theta$ . However, if one pays further attention to the process of recombination of the mother branes, one can easily understand why the final state of the brane produced does not wrap the same compactified space as the mother brane. The tension of the cosmic string does depend on the angle  $\theta$ , which is of course consistent with the analysis in the effective Lagrangian. The cosmological constraints are modified and will be relaxed by a factor of  $\theta$ .

## 2 String production after angled brane inflation

Let us start with a short review of angled inflation. Here we mainly follow ref.[14] for later convenience. In this section we consider string models that have 6 of the 9 space dimensions compactified, and  $D_p$ -branes in 10-dimensional space-time. Here the  $(p - 3)$  dimensions parallel to the  $D_p$ -branes are compactified with volume  $V_{\parallel}$ , and the  $d$  dimensions orthogonal to the  $D_p$ -branes are compactified with volume  $V_d$ . The remaining 3

dimensions of the  $D_p$ -branes are not compactified and they are the three spatial dimensions of the four-dimensional effective Lagrangian. Here we denote the string scale by  $M_s^2 \equiv \alpha'^{-1}$ . Here we will assume that only  $d_\perp$  dimensions of the orthogonal  $d$  dimensions are large, and the volume of the compactified 6-dimensional space is  $V = V_\parallel V_\perp V_{d-d_\perp}$ . The volume  $V_{d-d_\perp}$  is assumed to be  $V_{d-d_\perp} = (2\pi/M_s)^{d-d_\perp}$ . For simplicity, we will also assume that all the large extra dimensions have an equal size  $l_\perp = 2\pi r_\perp$ , which allows us to use  $V_\perp = (l_\perp)^{d_\perp}$  for the volume that is transverse to the  $D_p$ -brane. For the volume of the compactified space of the  $D_p$ -brane, we use  $V_\parallel$ .

String models with branes at angles have already been discussed by many authors. Here we consider angled  $D_p$ -branes where each brane is wrapping 1-cycles in a two dimensional torus that have radii  $r_\parallel$  and  $ur_\parallel$ , where  $u$  is a constant of  $u < 1$ .<sup>4</sup> Then the energy density of the brane is given by[14]

$$E_i = \tau_4 l_\parallel \left[ n_i^2 + (um_i)^2 \right]^{1/2}, \quad (2.1)$$

where the brane wraps a straight line in the  $n_i[a] + m_i[b]$  homology class, and  $\tau_p = \frac{M_s^{p+1}}{(2\pi)^p g_s}$ . Let us consider two angled  $D_p$  branes at a distance in the direction orthogonal to the torus. The angle  $\theta$  is given by  $\theta = \phi_1 - \phi_2$ , where  $\phi_i = \tan^{-1}(um_i/n_i)$ . When the distance is large, the effective potential for angled inflation is given by

$$V(y) = V_0 - \frac{\beta M_s^{6-d_\parallel} \sin^2 \theta / 2 \tan \theta / 2}{4\pi y^{d_\perp-2}} \quad (2.2)$$

for  $d_\perp > 2$ . Here  $\beta$  is a constant, and  $V_0$  is proportional to  $\tan^2 \theta$ . The potential becomes logarithmic when  $d_\perp = 2$ .

Cosmic strings would be produced due to tachyon condensation during recombination after angled inflation. Tachyon condensation generically allows the formation of lower-dimensional branes. The potential for the tachyon  $T$  is[14]

$$V_T \propto \text{tr}(TT^\dagger)(M_s^4 y^2 - 2\pi M_s^2 \theta), \quad (2.3)$$

for  $\theta \ll 1$ . From eq.(2.2) and eq.(2.3), one could easily understand the  $\theta$ -dependence of the cosmic strings,  $\mu \propto \theta$ . Thus, the calculation in the effective Lagrangian suggests that the tension of the cosmic string must be proportional to  $\theta$ .

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<sup>4</sup>For simplicity, we use  $u = 1$  in later calculations.

On the other hand, however, it is also suggested that the Kibble mechanism does not happen in compactified dimensions, so that cosmic strings would be formed by the  $D_{p-2}$ -branes wrapping the same compactified cycles as the original  $p$ -branes. The tension of such cosmic string is  $\mu = \frac{M_s^{p-1} V_{\parallel}}{(2\pi)^{p-2} g_s}$ , which cannot depend on  $\theta$ .

As we stated in the previous section, the two results are in contradiction, which must be explained clearly from the brane dynamics during recombination.

First we will naively assume that the produced cosmic strings are the  $D_{p-2}$ -branes that are stretched between final state of the  $D_p$ -brane, as is depicted in fig.1. Then the tension of the  $D_{p-2}$ -brane depends on the distance between branes, which is proportional to  $\theta$  for  $\theta \ll 1$ . If the supersymmetry breakings induced by other source branes at a distance are negligible, the final state of the angled inflation is the BPS state of a  $D_p$ -brane. On the basis of our assumption that the cosmic string corresponds to the stretched  $D_{p-2}$ -brane, the produced cosmic string will also be a BPS state. According to the discussion in ref.[21], the cosmic string that satisfies the BPS conditions is the D-term string in the effective Lagrangian. Thus, our assumption is consistent with the expectation that the angled inflation is described as a model of D-term inflation in the effective Lagrangian.<sup>5</sup> Thus our assumption, that the  $D_{p-2}$ -branes stretched between the final state of the  $D_p$ -brane are the cosmic strings in the effective Lagrangian seems appropriate to explain the  $\theta$  dependence.

However, to justify our assumption, we must answer why the tachyon condensation on the worldvolume of the original  $D_p$ -brane could have produced such a brane configuration during recombination after angled inflation. To explain our idea, first we will consider a bound state of a  $D_p$ -brane and a  $D_{p-2}$ -brane, which is depicted in fig.2. The  $D_{p-2}$ -brane would dissolve in the  $D_p$ -brane when the distance becomes small; however, the  $D_{p-2}$ -brane can be pulled out from the  $D_p$ -branes at the cost of energy. Let us consider a situation where a  $D_{p-2}$  brane is produced on the worldvolume of the original  $D_p$ -brane due to tachyon condensation. The initial configuration is schematically given in the left column of fig.3. Then recombination starts, and the  $D_{p-2}$ -brane is pulled out from the

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<sup>5</sup>An explicit calculation for the correspondence between the D-term string in the effective Lagrangian and the extended  $D$ -brane is given in ref.[9] for an inflation model due to Hanany-Witten type brane dynamics[10].

$D_p$ -brane as shown in the center of fig.3. The final state is given on the right of fig.3, where the dashed line denotes the  $D_{p-2}$ -brane that corresponds to the cosmic string in the effective Lagrangian. We think one can easily understand from fig.3 why the final state of the produced  $D_{p-2}$ -branes does not wrap the same compactified space as the original  $p$ -brane. The tension of the cosmic strings should depend on  $\theta$ , which is consistent with the expectation from the analysis from the effective Lagrangian.

Now we will examine if the tension of the D-term string that is calculated from the effective Lagrangian matches with the extended  $D_{p-2}$ -brane in the brane dynamics. Our assumption is that the cosmic string that would be produced after angled brane inflation corresponds to the extended  $D_{p-2}$ -brane. In this case, from the viewpoint of brane dynamics, the cosmic string becomes a BPS state of the four-dimensional effective Lagrangian. On the other hand, from the viewpoint of the effective Lagrangian, the string that satisfies the BPS conditions must be the D-term string, as is discussed in ref.[21]. Thus, if our assumption is correct, angled brane inflation must be a model of D-term inflation. Here we will consider a typical form of the Lagrangian for D-term inflation and calculate the tension of the D-term string. It is not a trivial task to examine if the tension of the D-term string obtained matches with the tension that is obtained from the brane dynamics. For simplicity, we will consider two  $D_4$ -branes on a two-dimensional torus, which is schematically depicted in fig.3. The radius of the torus is  $r_{||} = l_{||}/2\pi$ . Here we consider a generic form of the potential for D-term inflation[22],

$$V = g^2 \left( |\phi|^2 - \xi \right)^2. \quad (2.4)$$

Here the trigger field  $\phi$  is the tachyon. Terms that are irrelevant for our present discussions are neglected. Thus, the energy density during inflation is represented as

$$V_0 = g^2 \xi^2. \quad (2.5)$$

One can calculate the explicit form of the energy density  $V_0$  from the brane dynamics of angled inflation[14] for  $\theta \ll 1$ ,

$$V_0 = \frac{\tau_4 l_{||} \theta^2}{4}. \quad (2.6)$$

The tension of the D-term string in the effective Lagrangian is[21]

$$\mu_{D-string} = 2\pi\xi, \quad (2.7)$$

where the gauge coupling  $g$  in the effective Lagrangian is given by[14]

$$g^{-2} = \frac{M_s r_{\parallel}}{2\pi g_s}. \quad (2.8)$$

From eqs.(2.5), (2.6), (2.7) and (2.8), one can calculate the tension of the D-term string in the effective Lagrangian.

On the other hand, from the pure brane dynamics, we can calculate the tension of the cosmic string that corresponds to the extended  $D_2$ -brane. If the angle  $\theta$  is small, i.e.,  $\theta \ll 1$ ,

$$\mu_{D_2} = \frac{1}{(2\pi)^2} \frac{M_s^3 (l_{\parallel}/2) \theta}{g_s}. \quad (2.9)$$

It is now clear that the tension of the D-term string matches the tension calculated from the extended  $D_2$ -brane.

### 3 Conclusions

We have examined string production after angled brane inflation. First, we pointed out that there has been a discrepancy between the expected tension of the cosmic string calculated from the viewpoint of the four-dimensional effective Lagrangian and the one obtained from the brane tension of the daughter brane. If the cosmic string is a lower-dimensional daughter brane that wraps the same compactified space as the original mother brane, the tension of the string cannot depend on the angle. On the other hand, from the analysis of the effective Lagrangian, it is easy to see that the tension of the cosmic string must be proportional to  $\theta$  for  $\theta \ll 1$ . This is the problem we have solved in this paper. Our idea is shown in fig.3. We have calculated the explicit form of the tension of the cosmic string, and compared the two results.

The cosmological constraint for angled inflation will be relaxed because the expected tension of the cosmic string becomes smaller than the one obtained in the previous arguments by a factor of  $\theta$ .

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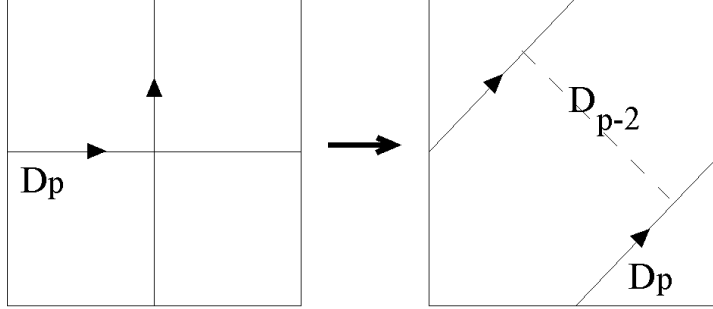


Figure 1: Recombination of the two-brane system on a two-dimensional torus. The dashed line is the  $D_{p-2}$ -brane that corresponds to the cosmic string in four-dimensional space-time.

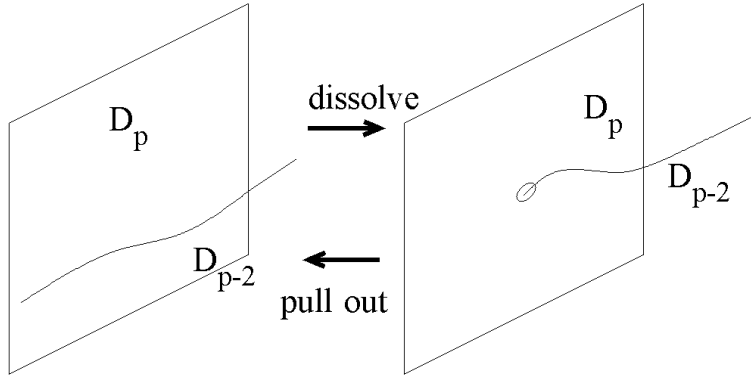


Figure 2: Bound state of  $D_p$ -brane and  $D_{p-2}$ -brane. In the right picture, the  $D_{p-2}$ -brane is dissolved in the  $D_p$ -brane. The dissolved  $D_{p-2}$ -brane can be pulled out of the  $D_p$ -brane, although the process costs energy.

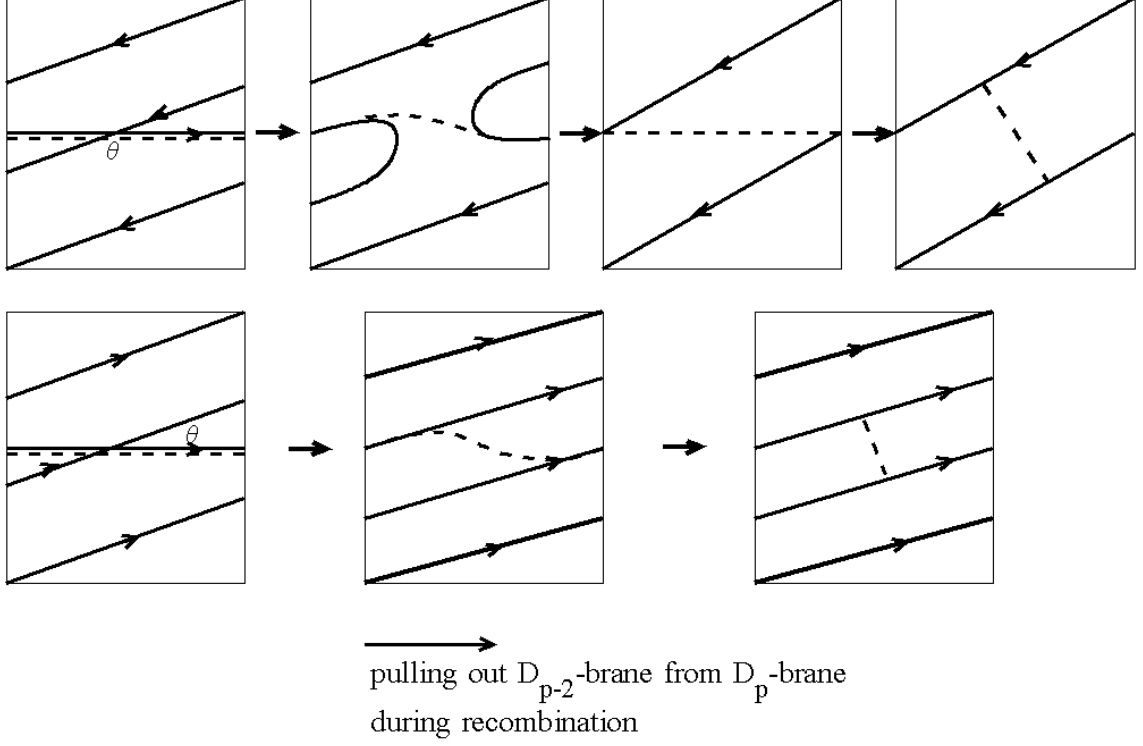


Figure 3: Upper row: schematic recombination of two  $D_p$ -branes with  $(\pi - \theta) \ll 1$ . The dashed line on the  $D_p$ -brane represents the  $D_{p-2}$ -brane that might appear on the worldvolume of the  $D_p$ -brane when the tachyon condenses. Second row: schematic recombination of two  $D_p$ -branes with  $\theta \ll 1$ . In both cases, the  $D_{p-2}$ -brane is pulled out of the  $D_p$ -brane. As a result, the daughter  $D_{p-2}$  brane does not wrap the same compactified space as the mother brane. Thus, for the angled inflation model, the cosmic strings can depend on  $\theta$ , which is the property required from analysis of the effective Lagrangian.